DEFORMATION BEHAVIOR OF UNALLOYED VANADIUM - D.T. Hoelzer and A. F. Rowcliffe

OBJECTIVE

The broad objective of this work is to investigte the influence of the interstitial elements on the deformation behavior of BCC alloys.

SUMMARY

The tensile deformation behavior of unalloyed vanadium has been determined at 200°C and 300°C for strain rates in the range 10^{-1}/s to 10^{-5}/s. The occurrence of serrated flow effects in the Lüders extension and work hardening regimes of tensile stress-strain curves is associated with negative strain rate sensitivity of stress parameters.

PROGRESS AND STATUS

Introduction

The work described here is from a study of the deformation behavior of vanadium and is a continuation of an investigation of the strain rate sensitivity of V-4Cr-4Ti (No. 832665). In previous studies [1-3], the deformation behavior of the V-4Cr-4Ti alloy was shown to exhibit dynamic strain aging (DSA) during tensile testing, typically at temperatures ranging from 300°C to 750°C and strain rates ranging from 10^{-1}/s to 10^{-5}/s. Dynamic strain aging has been observed by the appearance of serrated yielding (continuous) and jerky flow (discontinuous) in the Lüders strain and work hardening regimes of stress strain curves and a concomitant negative value in strain rate sensitivity (SRS) for flow stresses. The shape, spacing, and magnitude of the serrations and jerky flow depended on temperature, strain, and strain rate.

Dynamic strain aging is associated with the migration of interstitial and substitutional solute atoms to dislocations during deformation [4,5]. Interstitial atoms have a dominant effect on DSA at low temperatures due to their higher diffusion coefficients compared to substitutional atoms. In the V-4Cr-4Ti alloy, DSA was attributed to interstitial O, C, and N at temperatures below ~500°C since Ti and Cr solute atoms are generally immobile below this temperature. Although interstitial atoms can be removed from solid solution by forming Ti-OCN precipitates a sizable fraction remain in solution since DSA was observed in the alloy at 300°C. In order to investigate the interaction between Ti solute atoms and interstitial atoms, an investigation was conducted on the unalloyed vanadium used in the production of the 500kg heat of V-4Cr-4Ti. The reason for using this vanadium was to ensure a similar interstitial content with V-4Cr-4Ti but without the Ti and Cr alloying atoms. The purpose of this study is to investigate the temperature range of DSA in vanadium in order to develop a better understanding of the Ti-OCN precipitation process and the interaction between Ti and interstitial atoms.

Experimental Procedure

Sheet tensile specimens of the type SS-3 (nominal gage dimensions 0.76 × 1.52 × 7.6 mm) were prepared from unalloyed vanadium (Teledyne Wah-Chang heat no. 832665). A 0.25in thick plate was cut from the vanadium ingot, hot rolled at ~1050°C to a thickness of 0.10in (60% reduction) and then cold rolled to 0.06in (40% reduction). Specimens were electro-discharge machined from the 0.06in thick plate and annealed at 1000°C for 1 hour in a vacuum of <~3×10^{-7} torr followed by furnace cooling. This procedure resulted in a uniform microstructure consisting of recrystallized grains with an average grain size of 89±5μm, which is shown in Figure 1. Tensile testing was carried out under a vacuum of ~2×10^{-7} torr using a screw-driven machine. Specimens

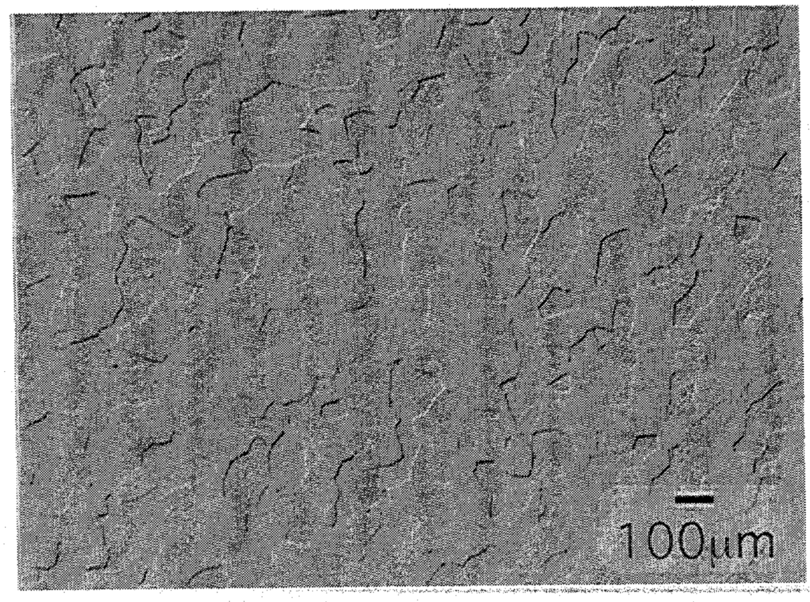

Figure 1. Light micrograph of vanadium annealed at 1000°C.

were held at the test temperature for 20-30 minutes before starting the test. Data were acquired digitally at rates of 20 points per second (pts) for tests conducted at 10^{-1}/s and 10^{-3}/s strain rates and 0.2pts at 10^{-5}/s strain rate.

Results

Data obtained from testing the specimens at 200°C and 300°C with strain rates of 10^{-1}, 10^{-3}, and 10^{-5} are summarized in Table 1. The engineering stress-strain curves for 200°C and 300°C are shown in Figures 2 and 3, respectively. The curves have been offset along the normalized crosshead displacement axis for comparison of the elastic and Lüders extension regimes. The results show Lüders extensions typically ranging from 0.4 to 1.4% following an initial yield stress, σ_i, in all of the specimens. A small permanent strain of the order of 0.1 to 0.2% usually occurred after σ_i. Serrations associated with the Lüders extension are propagated by an average stress

Table 1. Temperature and Strain Rate Dependence of Unalloyed Vanadium Tensile Properties.

Specimen	Test Temp.	Strain Rate	Initial Yield Stress σ_i	Lower Yield Stress σ_y	Ultimate Tensile Strength σ_u	Stress for 8% Strain σ_s	Luders Strain ε_L	Uniform Strain ε_u	Total Strain ε_t
ID	°C	s^{-1}	MPa				%		
PV46	200	10^{-1}	93	124	193	172	1.4	29.0	42.8
PV44	200	10^{-3}	105	105	188	161	0.8	24.1	36.2
PV45	200	10^{-5}	88	100	194	187	0.8	11.1	17.6
PV41	300	10^{-1}	90	116	183	174	0.4	14.2	20.6
PV42	300	10^{-3}	105	115	240	213	0.8	15.2	21.1
PV43	300	10^{-5}	118	118	297	238	1.4	19.4	27.8

which is defined as the lower yield stress, σ_y. Upon completion of the Lüders extension, the deformation proceeds with initially an increase in the work hardening rate on the stress-strain curve that eventually decreases until the ultimate stress, σ_u, is achieved. Tests performed at high temperatures and/or low strain rates exhibited both continuous (serrated yielding) and discontinuous (jerky flow) behavior in the plastic flow regimes of stress strain curves. These types of deformation are related to the phenomenon of dynamic strain aging (DSA). The results indicated that both the shape and magnitude of the serrations changed with temperature, strain, and strain rate. For tests carried out at a rate of 10^{-1}/s, the data acquisition system was not sufficiently rapid to detect load drops associated with the serrations. Therefore, determination of jerky flow could not be ascertained at this strain rate.

The testing temperature had an effect on the dependency of elongation with strain rate. At 200°C, the largest elongations (uniform and total) occurred at a rate of 10^{-1}/s and the smallest at

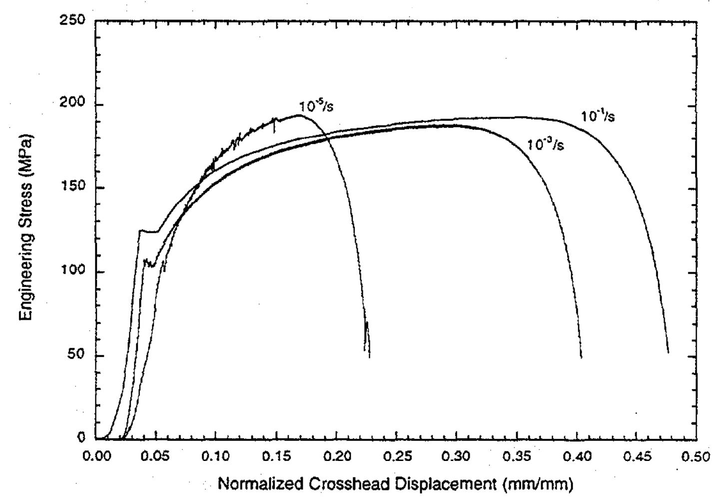

Figure 2. The stress-strain curves for vanadium at 200°C.

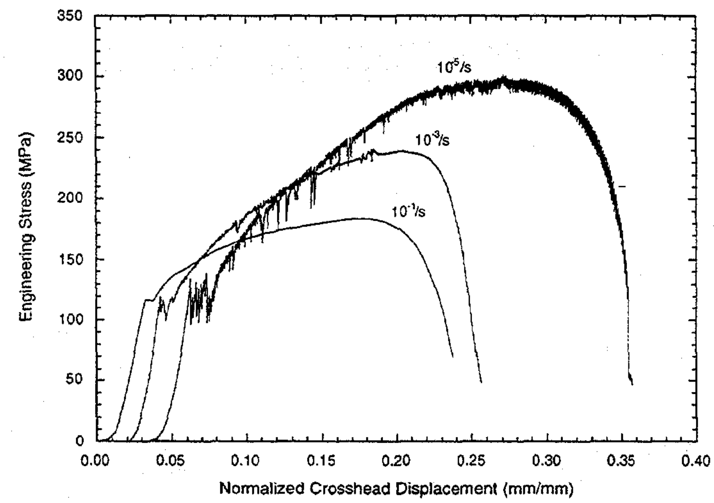

Figure 3. The stress-strain curves for vanadium at 300°C.

10^{-5}/s (Fig. 2). This was opposite to that at 300°C, which showed the largest elongations at 10^{-5}/s and the smallest at 10^{-1}/s (Fig. 3).

The strain-rate dependence was determined for the lower yield stress, σ_y, and for a parameter, σ_s, which is the stress required to produce a strain of 8% after the completion of the Lüders extension. The 8% strain is an arbitrary value selected to represent material in the strain-hardening regime. The strain-rate sensitivities of these parameters are presented in Figures 4 and 5.

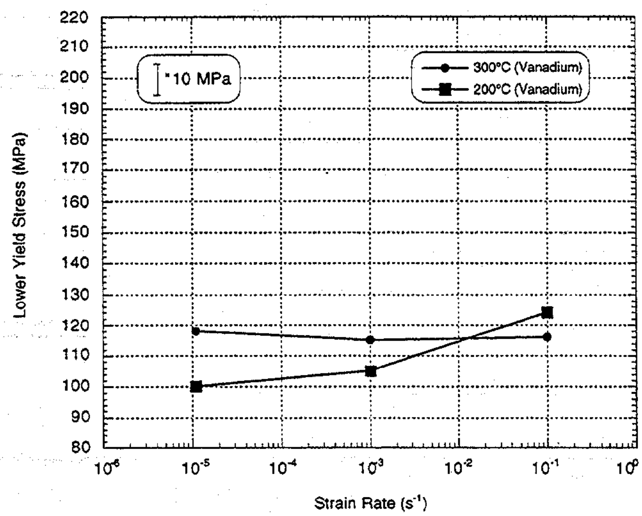

Figure 4. Effect of strain rate on the lower yield strength of vanadium tested at temperatures of 200 and 300°C.

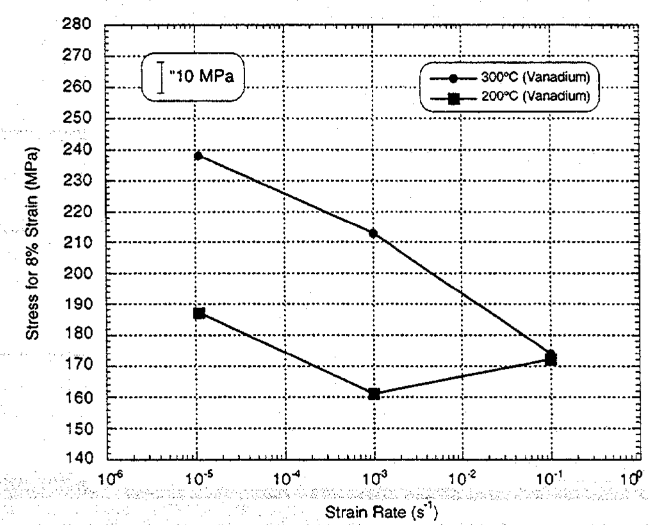

Figure 5. Effect of strain rate on the tensile strength (measured at 8% strain in the strain-hardening regime) of vanadium tested at temperatures of 200 and 300°C.

The data shows that changes in temperature, strain, and strain rate produced significant variations in strain rate sensitivity, m, of vanadium, where m is defined as

$$m=\frac{1}{\sigma}\frac{\partial\sigma}{\partial \ln\dot{\varepsilon}}\bigg|_{\varepsilon,T}$$

where σ is the stress and $\dot{\varepsilon}$ is the strain rate. Figure 4 shows that σ_y exhibits a positive SRS at 200°C (m = 0.023), but is virtually independent of strain rate at 300°C (m = -0.002). A different behavior in SRS was observed for the σ_s (Fig. 5). At 200°C, the SRS of σ_s transitions from a positive value over the range 10^{-1} to 10^{-3}/s to a negative value as the strain rate is decreased below ~10^{-3}/s. A negative value for m was observed at 300°C (m = -0.034) for the full range of strain rates examined.

The appearance of serrations and jerky flow in stress-strain curves at 200°C (Fig. 2) and 300°C (Fig. 3) coincided with negative values for m of σ_s. From these figures, jerky flow is observed at 200°C for the strain rate of 10^{-5}/s while at 300°C it is observed for strain rates at 10^{-3}/s and 10^{-5}/s. It is possible that serrations or jerky flow were present at 300°C for the strain rate of 10^{-1}/s, but was not resolved due to the data acquisition problem described above. These observations of the deformation behavior correlated with the negative value of m at 300°C (m = -0.034) for strain rates ranging from 10^{-1}/s to 10^{-5}/s and at 200°C for strain rates below 10^{-3}/s.

Discussion

The phenomenon of strain aging (static and dynamic). arises in vanadium due to the segregation of interstitial carbon, nitrogen, and oxygen solutes to dislocations to form Cottrell atmospheres [4,6,7]. In vanadium, these interstitial solutes have moderate solubility levels and high diffusion coefficients, which allows them to be mobile at low temperatures [8]. The results showing serrated yielding and jerky flow in stress strain curves at 200°C and a strain rate of 10^{-5}/s (Fig. 2) are consistent with these assessments of vanadium. An analysis of the jerky flow in the stress strain curve obtained at 200°C and 10^{-5}/s indicated that the average time duration between yield drops was ~129sec. This duration represents the time it takes for a sufficient number of interstitial atoms to diffuse to dislocations to form atmospheres, which either pins or subjects a drag on them, and for the dislocation to then break free with an increase in stress. Using the diffusion data for C, N, and O in vanadium [8], it was determined that only C and O possessed limited mobilities at 200°C, with calculated diffusion lengths for ~129sec of 4nm (C) and 2.9nm (O). These values are for bulk diffusion and should be larger for diffusion along dislocation cores. At 300°C and a strain rate of 10^{-5}/s (Fig. 3), the frequency of the serrations increases and the calculated time duration between the yield drops decreases to ~37.5sec. This decrease in time is due to the increased mobilities for the interstitial solutes. The calculated diffusion distance for a time duration of 37.5sec is 28.7nm (C), 22.8nm (O), and 2.2nm (N). From these calculations, the interstitial atoms responsible for causing DSA in vanadium at 200°C and 300°C are interstitial O and C atoms in solid solution. Contributions to DSA in vanadium by N should occur only at temperatures above 300°C.

The correlation between the appearance of serrations and jerky flow in stress strain curves and negative values of strain rate sensitivity, m, is consistent with previous investigations of strain aging effects in vanadium [6,7]. The results showed that this correlation occurred at 300°C for the full range of strain rates (m = -0.034 for σ_s at 10^{-1}/s to 10^{-5}/s) and at 200°C for strain rates below 10^{-3}/s. A negative m value was also measured for the ultimate stress, σ_u, at 300°C, which was -0.053. Systematic studies by Bradford and Carlson [6] and Thompson and Carlson [7] have shown that oxygen and nitrogen, respectively, can cause strain aging in vanadium but that the minimum values in m are smaller and occur at higher temperatures compared to the results of this study. Bradford and Carlson [6] observed serrations in stress strain curves along with negative values of m (σ_u) in vanadium containing 265 wppm O and 150 wppm C for temperatures ranging from 175°C - 425°C. They measured a minimum value in m of -0.023 at 340°C. A similar correlation was observed by Thompson and Carlson [7] in vanadium containing 210 wppm N for temperatures ranging from 250°C - 550°C, with a minimum value in m of -0.011 at 400°C. The reason for these differences is related to the interstitial content in vanadium. It was determined from chemical analysis that the vanadium plate used to make the SS-3 specimens contained 340 wppm O, 177 wppm N, and 198 wppm C, or a total interstitial content of 715 wppm. This level is higher than the combined C, N, and O contents of vanadium used by Bradford and Carlson and by Thompson and Carlson, which were 420 wppm and 365 wppm, respectively, for the vanadium cited above. Additional tensile tests will be performed on vanadium at temperatures above 300°C, which pertain to temperatures that DSA has been observed in the V-4Cr-4Ti alloy.

For temperatures investigated in this study, results showing differences in the SRS of σ_s for strain rates between vanadium and V-4Cr-4Ti [1-3] suggest that Ti and Cr solutes raise the temperature range over which DSA occurs by ~100°C. This was determined from the u-shape dependence of σ_s (and σ_u) on changes in strain rate that was observed for vanadium at 200°C (Fig. 5) and for V-4Cr-4Ti at 300°C (see Fig. 3 in ref. 2). For the SRS of σ_s, m was -0.034 for vanadium and was within the range between -0.014 to -0.021 for V-4Cr-4Ti at all test temperatures (i.e 400°C to 700°C). These results indicate that interstitial atoms are removed from solid solution by interacting with the solutes such as Ti to form precipitates. However, the effectively lower interstitial content of V-4Cr-4Ti can account for less negative values of m but cannot account for differences in the temperature range showing the DSA effect. This behavior suggests that an interaction occurs between Ti and interstitial solutes that decreases the mobility of the interstitials at temperatures below ~500°C, which is the temperature that Ti solutes start to become mobile. Further research using stereology to determine the volume fraction of precipitates is currently being performed on V-4Cr-4Ti in order to estimate the amount of interstitials in solid solution and to quantify their contribution to the DSA effect.

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